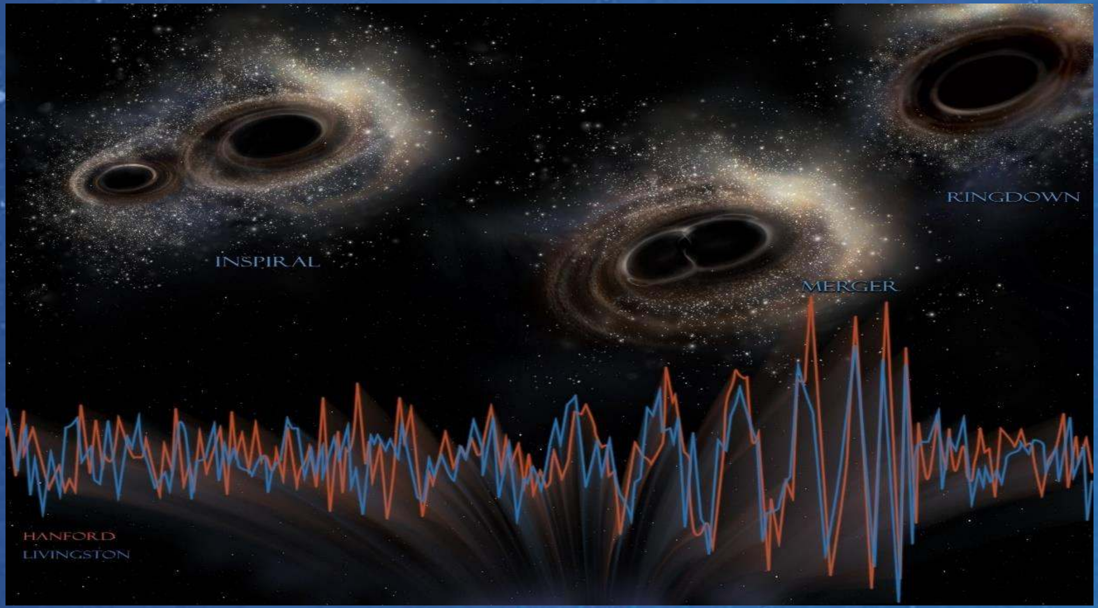
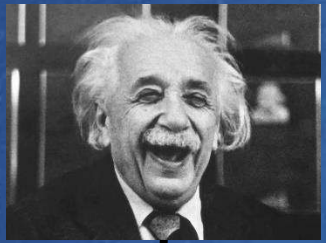


Improvement of the gravitational wave detector Virgo using squeezed states of light

Rencontres des Jeunes Physiciens- Pierre Gruning 23/11/2018

Gravitational waves: a brief history

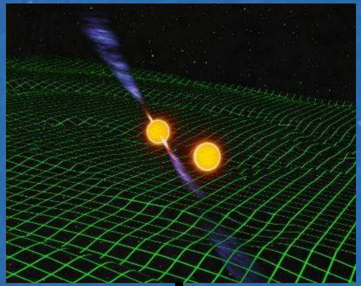


1918

A. Einstein
Über Gravitationswellen

Weber bars

1968

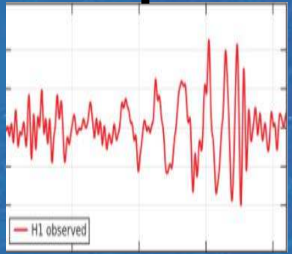


1974

1st indirect detection;
Hulse-Taylor Pulsar
(Nobel prize)

1st detection!

14th September 2015



3rd December 2015

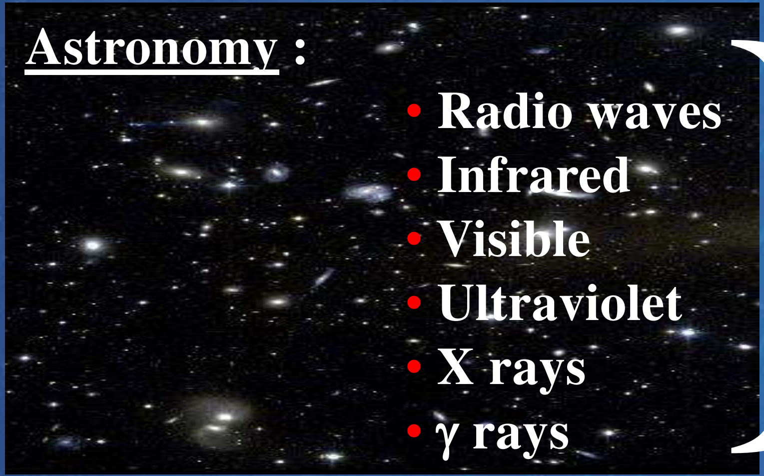
Launch of LISA Pathfinder

- 1st detection with 3 detectors
- 1ere observation of binary NS
- 1 EM counterpart
- Nobel prize

2017

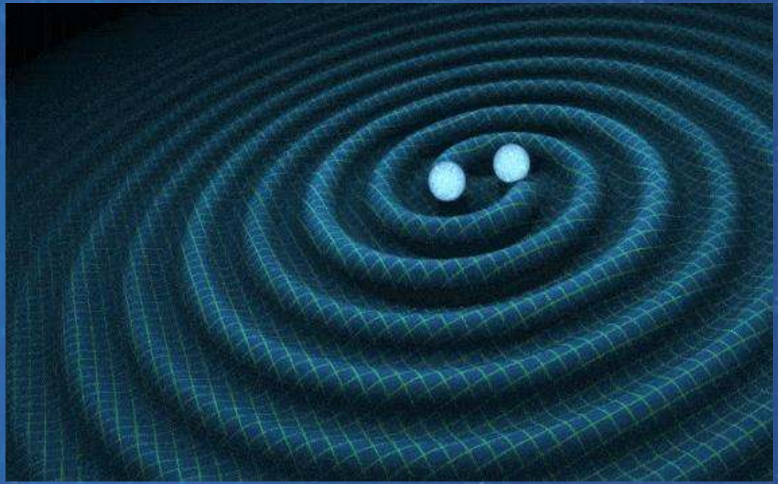
eLISA
2034 ?

Gravitational waves



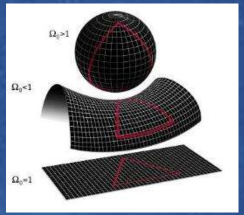
Electromagnetic waves
emitted by
moving
electric charges
or nuclear reactions

Gravitational waves
are emitted by moving masses



- Test General Relativity in a new domain
- Open a new window on the universe
    - Measure directy masses of detected objects
    - Observe black holes
    - Access to the core of violent events: supernova, gamma ray bursts …
    - Measure the geometry of the Universe with new probes



A gravitational wave generator on earth

source	distance	*h*
Steel bar, 500 T, ∅ = 2 m L = 20 m, 5 tours/s	1 m	$h=10^{-34}$: a distance of 1 km is stretched by 10^{-31} m
Bomb H 1 megaton (50x Hirosh.) Asymetry 10%	10 km	$h=10^{-29}$: a distance of 1 km is stretched by 10^{-26} m

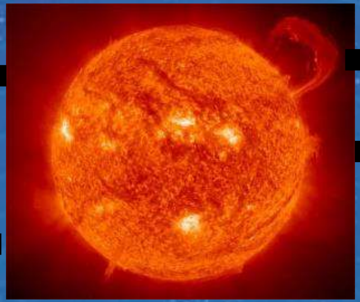
10 million billion times smaller than the atomic nucleus

10 billion times smaller than the atomic nucleus

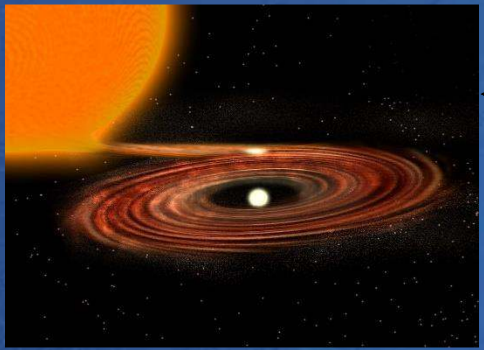
→ **Not detectable**

⇒ Only cataclysmic astrophysical phenomenons can emit detectable gravitational waves

Astrophysical and cosmological sources of gravitational waves



Supernova

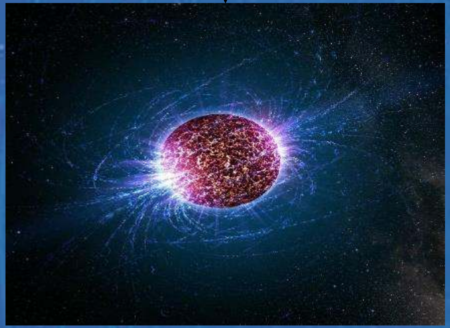


White dwarf

1,4 solar masses

1.10^9 kg/m^3

x 2000



Neutron star

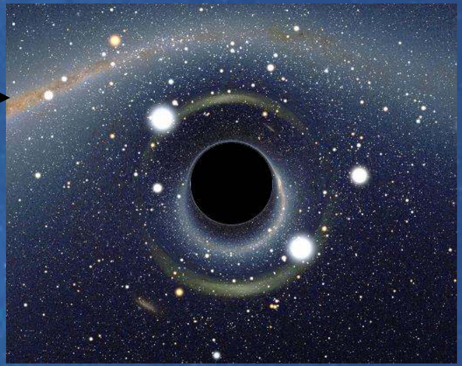
Up to 3 solar masses

6.10^{17} kg/m^3

X 1000 billion

Hypothetical states

- Quark star
- Preon star
- Electroweak star
- Etoile à bosons
- Etc.



Black hole

Biggest known: 66 billion solar masses

More « exotic » sources

- Pre-inflation quantum fluctuations
- Phase transition in the primordial universe
- Cosmic strings

Astrophysical and cosmological sources of gravitational waves

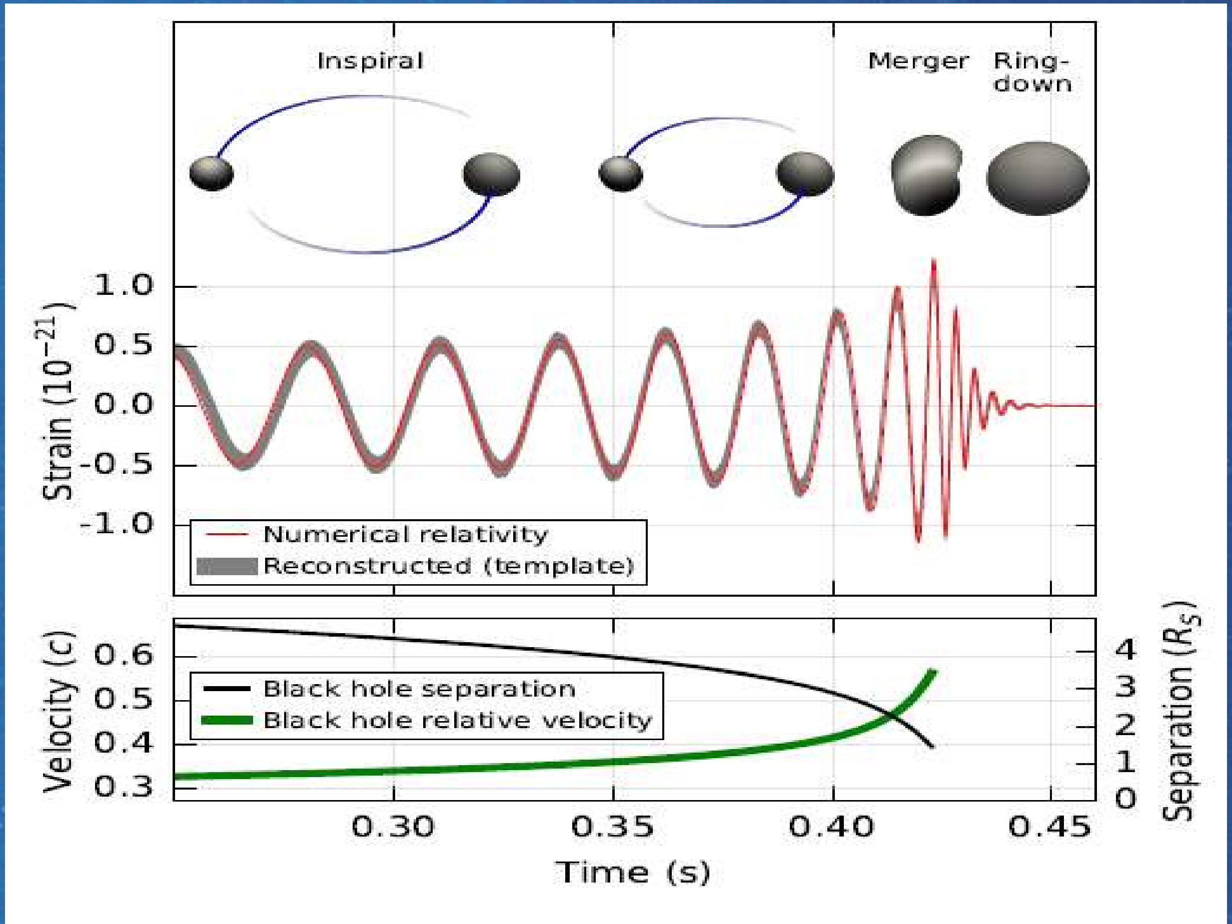
source	distance	*h*
Supernova 10 $M_\odot$ asymetry 10^{-5}	10 kpc	$h=10^{-21}$: a distance of 1 km is stretched by 10^{-18} m
Coalescence de 2 trous noirs de 1 $M_\odot$	10 Mpc	$h=10^{-20}$: a distance of 1 km is stretched by 10^{-17} m

« Only » 100 to 1000 times
smaller than the atomic nucleus

⟶ Détectable

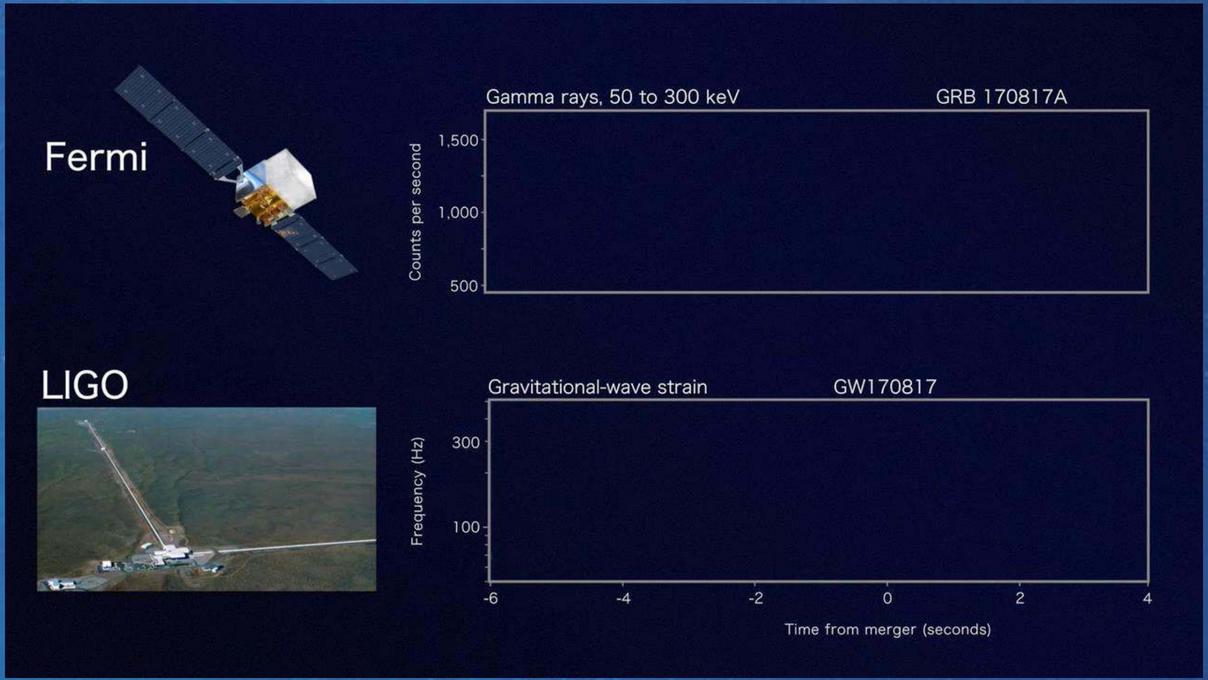
GW150914

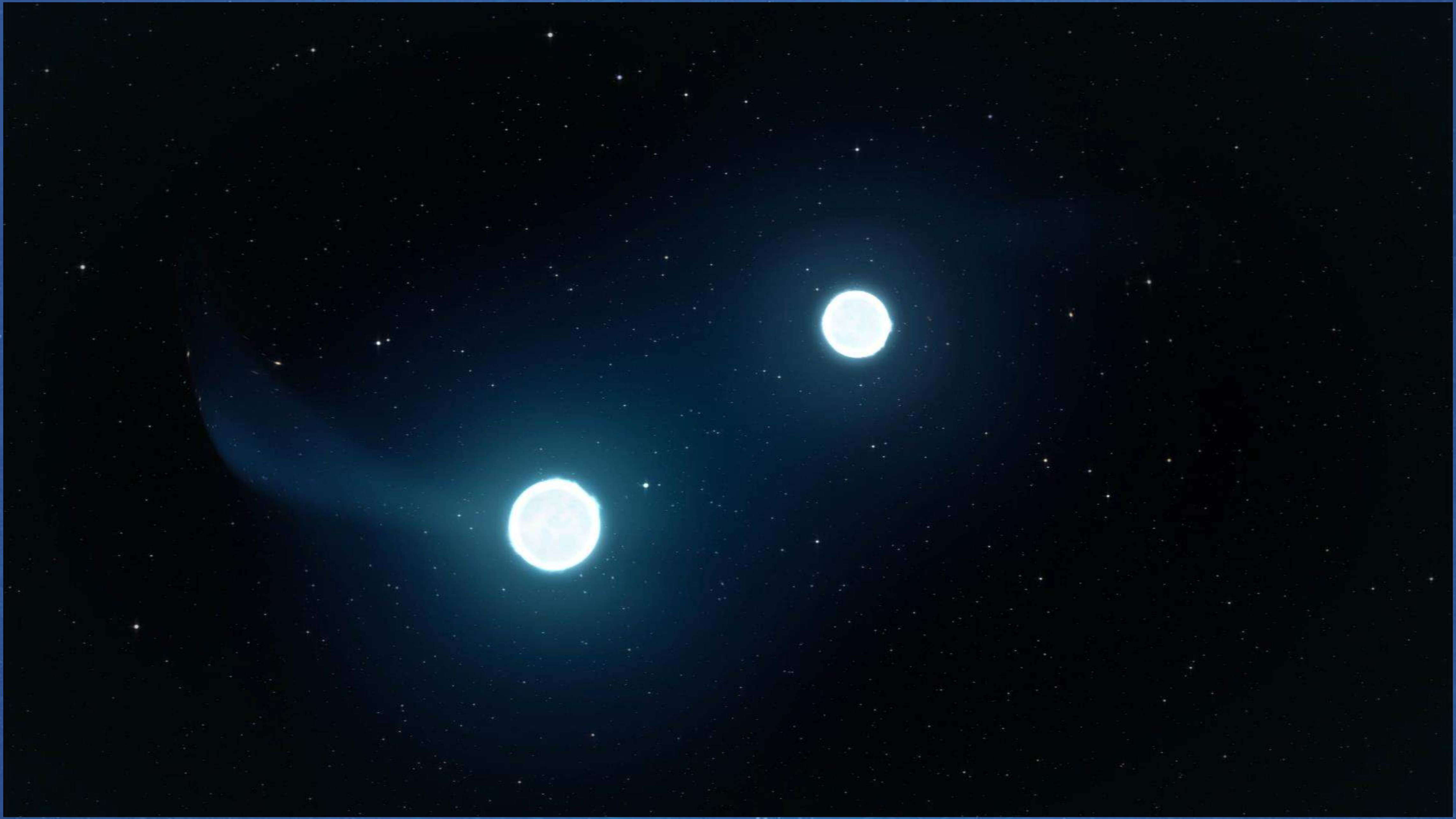
- **Masses initiales :**
  - **Trou Noir 1 : entre 32 et 41 M_{Sol}**
  - **Trou Noir 2 : entre 25 et 33 M_{Sol}**
- **Masse Finale : entre 58 et 67 M_{Sol}**
- **Energie Emise : entre 2,5 et 3,5 M_{sol}**
- **Probabilité que cela soit un faux signal < 1 sur 5 millions**



GW170817

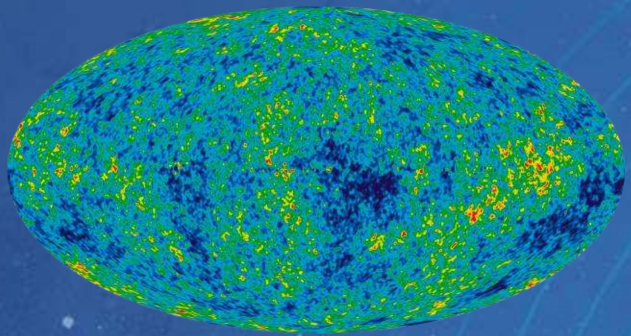
130 million years ago: a fusion of 2 neutron stars

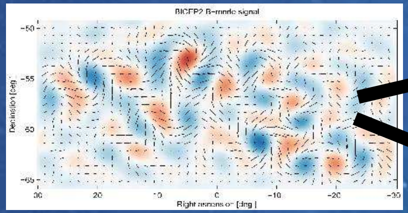


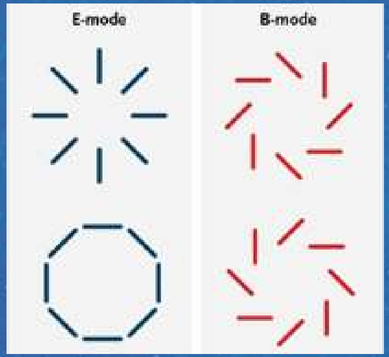


How to detect them ?

CMB polarization



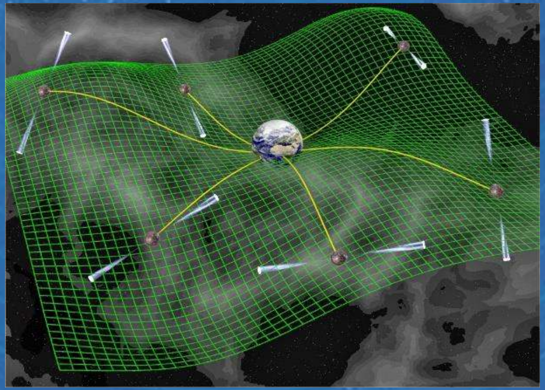




Polarization of B-modes in the CMB: Looking at the direction of oscillation of the first light emitted 380 000 years after the Big Bang

Weber bars

Trying to detect the deformation of bars becoming resonant when crossed by a gravitational wave

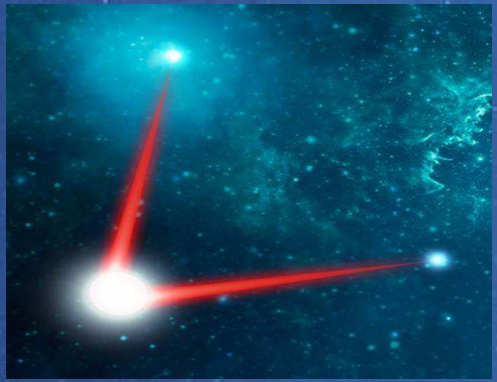


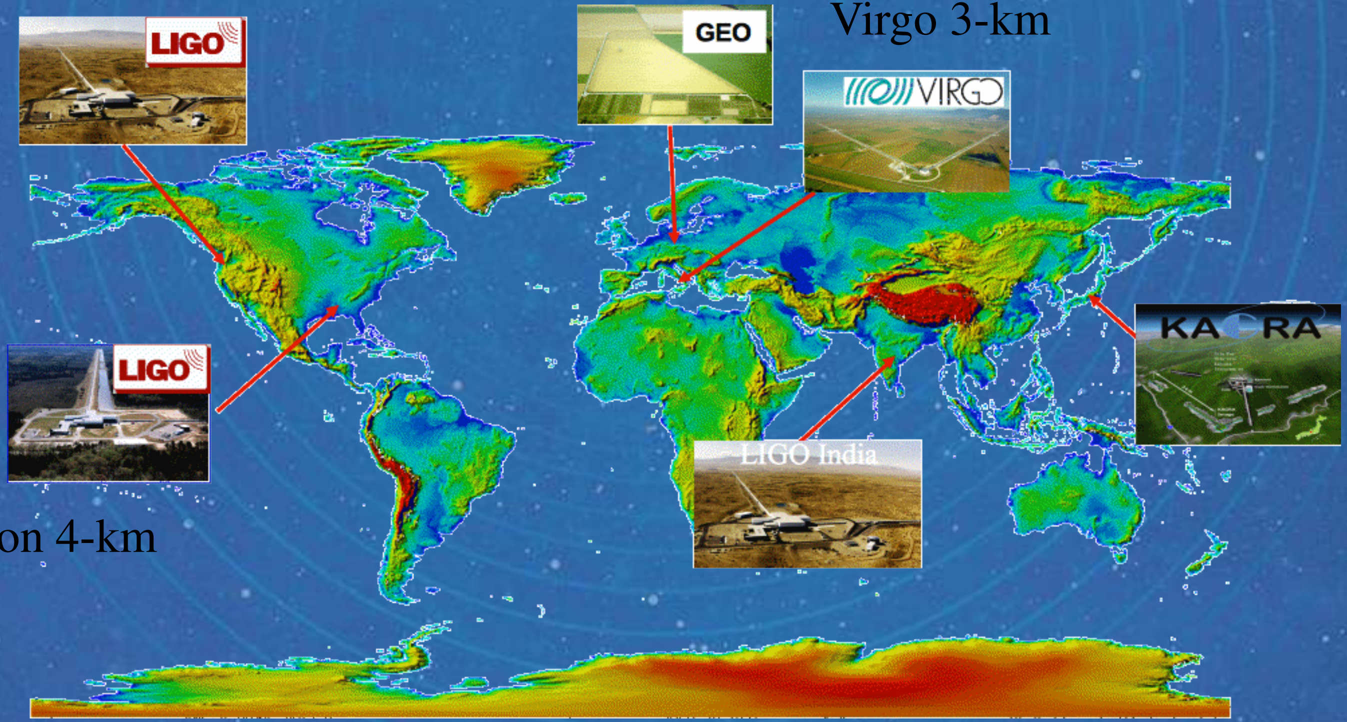
PTA (Pulsar Timing Array)

Measuring the arrival time of a pulsar signal at different periods during the year. For example the signal arrives 20 ns later in july and 20 ns earlier in january

How to detect them ?

Laser interferometry

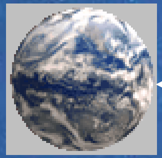




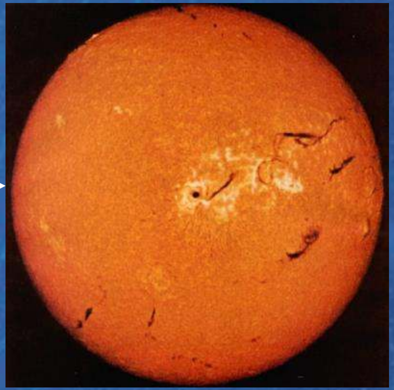
How to detect them ?

Distances have to be measured with a precision equivalent of 10^{-21}

A distance of 150 million km measured with a precision better than the size of an atom



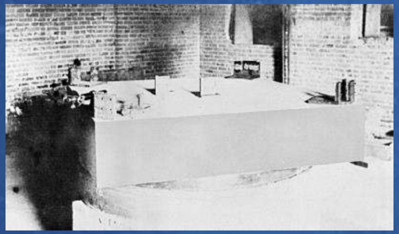
Earth

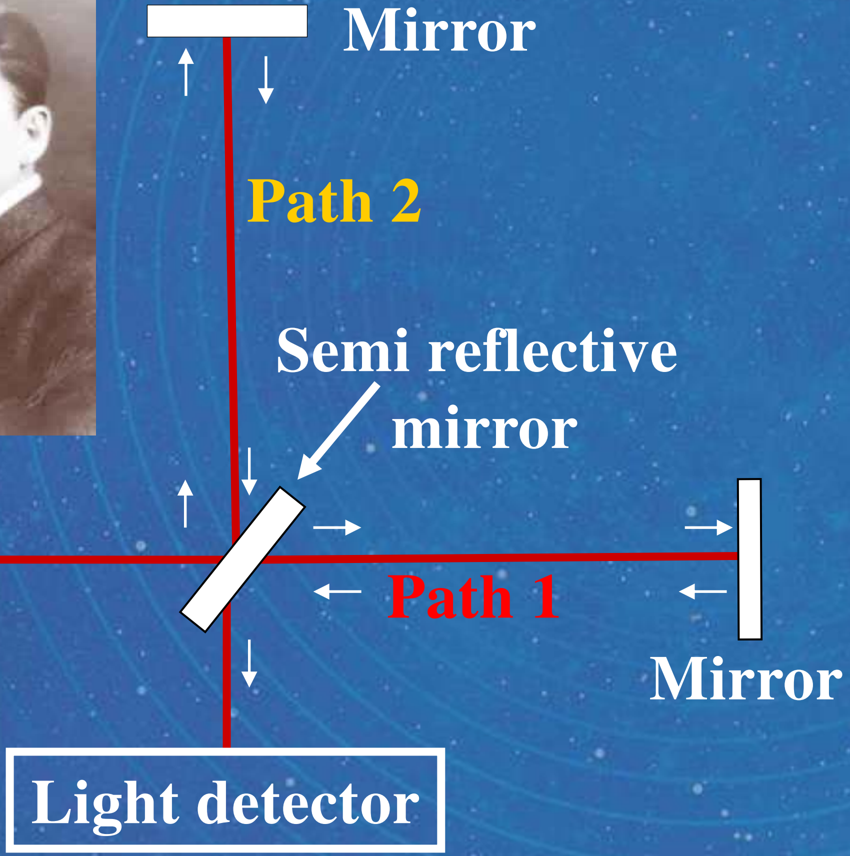


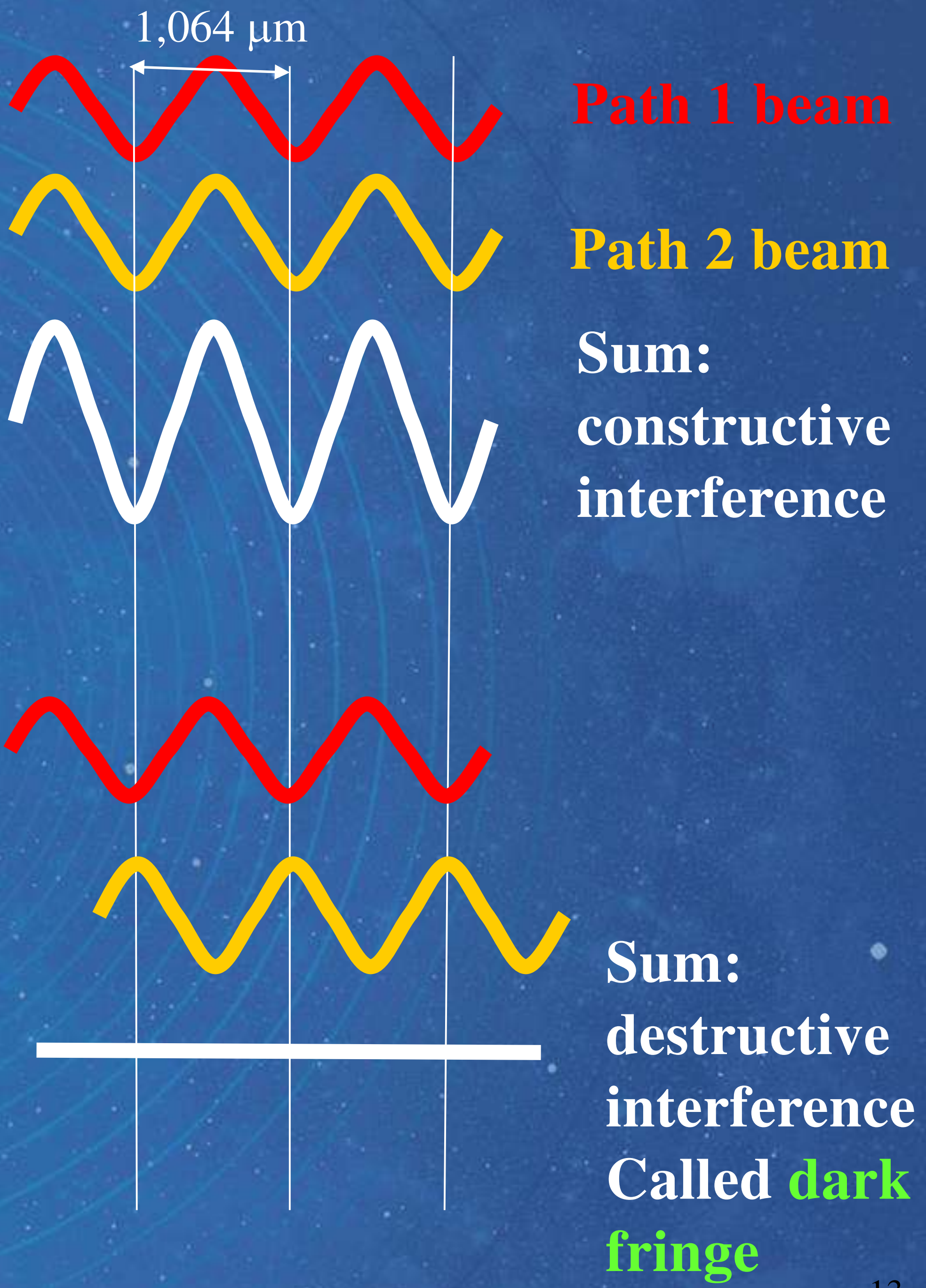
Sun

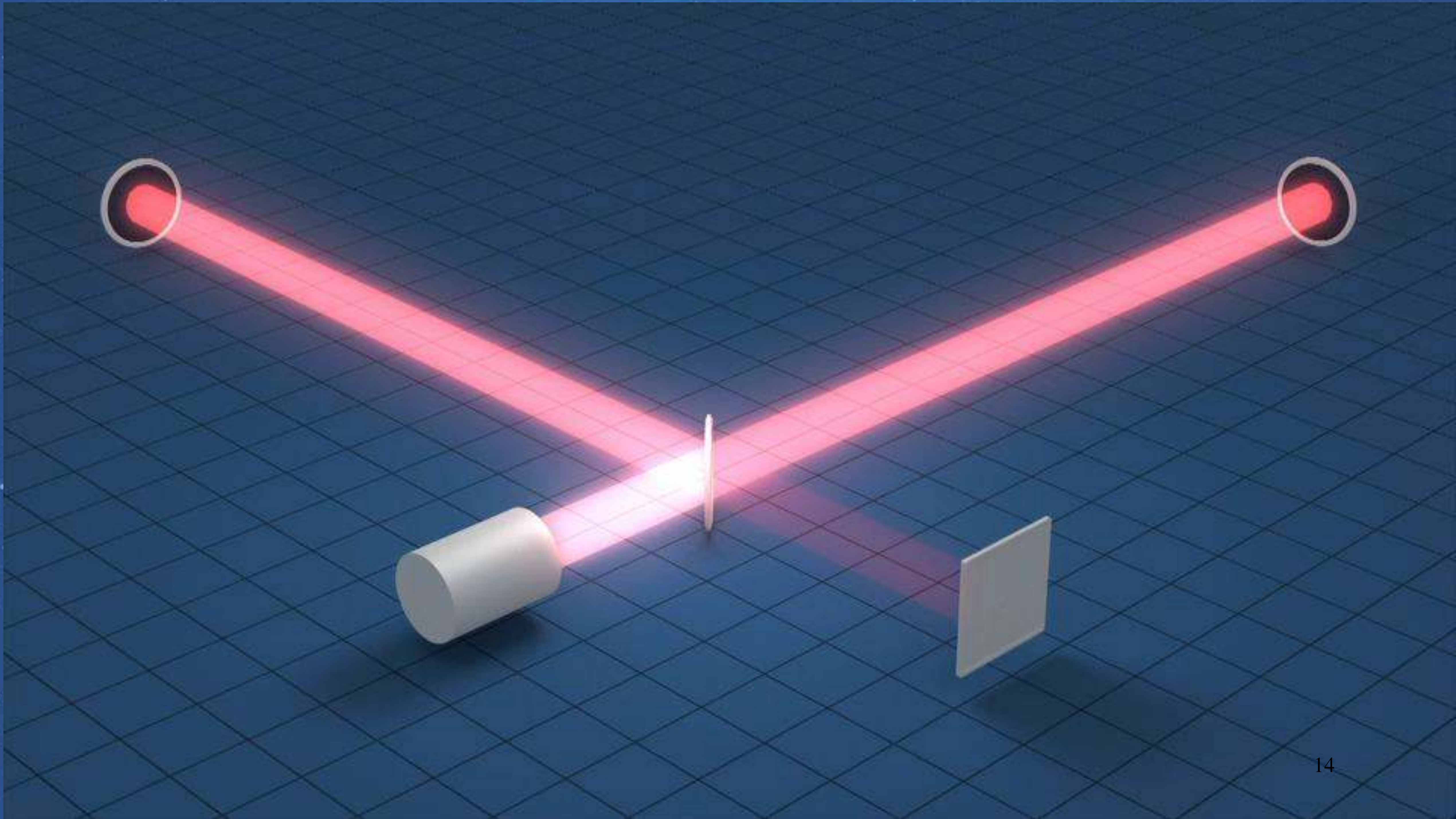
Interferometric detection

Michelson interferometer

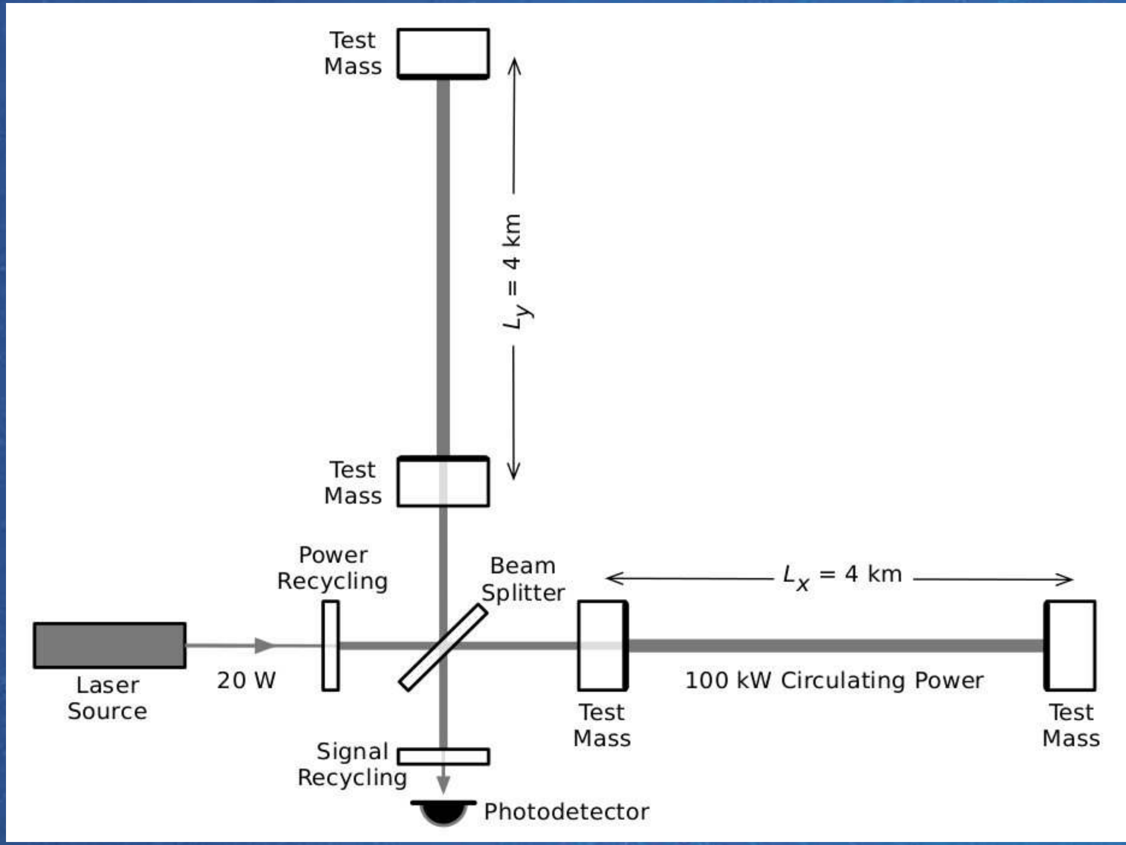


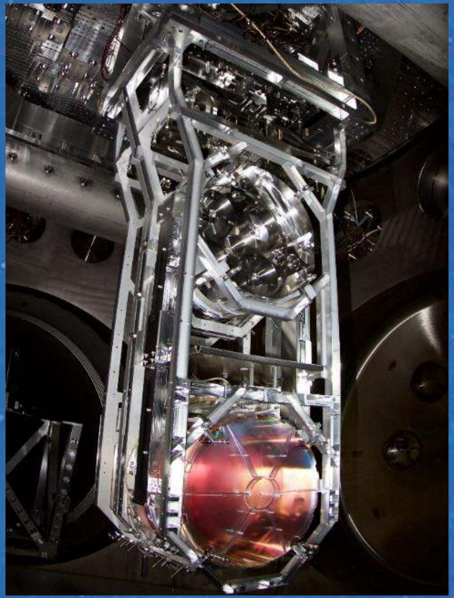






LIGO and Virgo detectors





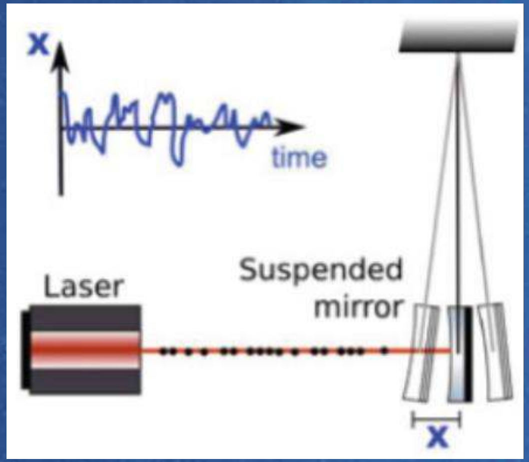
Control the relative position of the mirrors with a precision better than a millionth of a micron

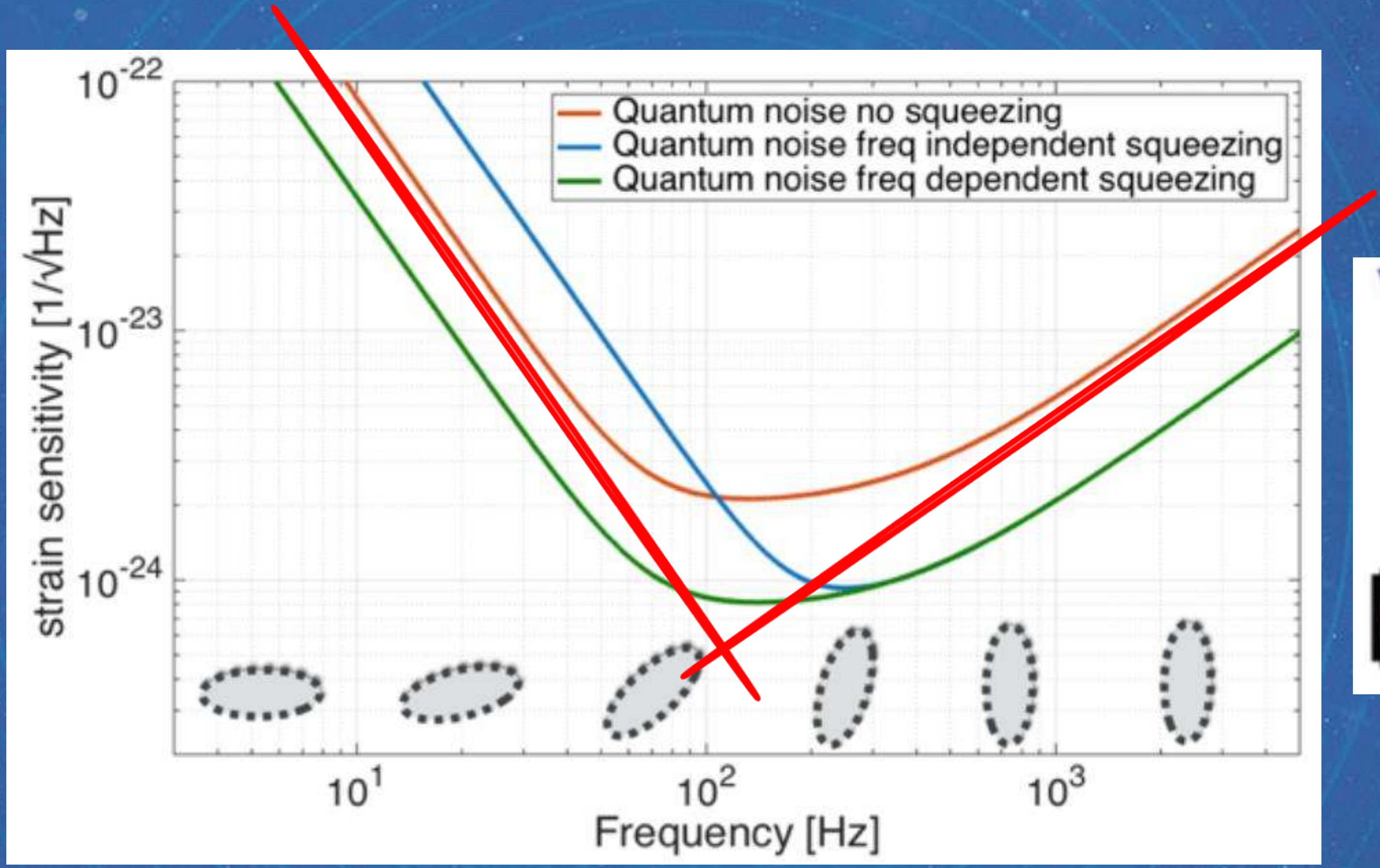
Isolate from ground vibrations

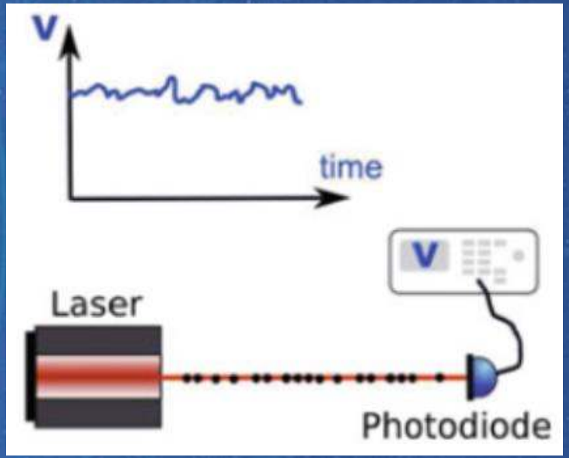
Using mirrors which quality is at the limit of current technology

Put the whole interferometer (thousands of m^3) under vacuum ($P = 10^{-9}$ mbar)

Improving interferometers beyond the standard quantum limit

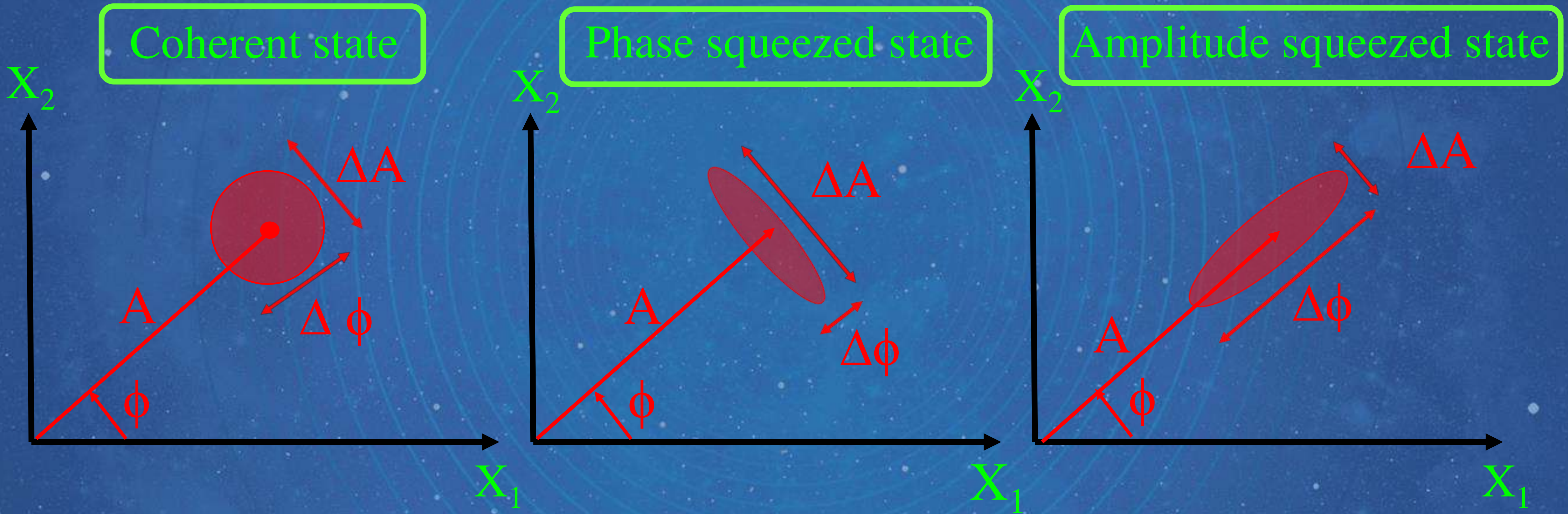






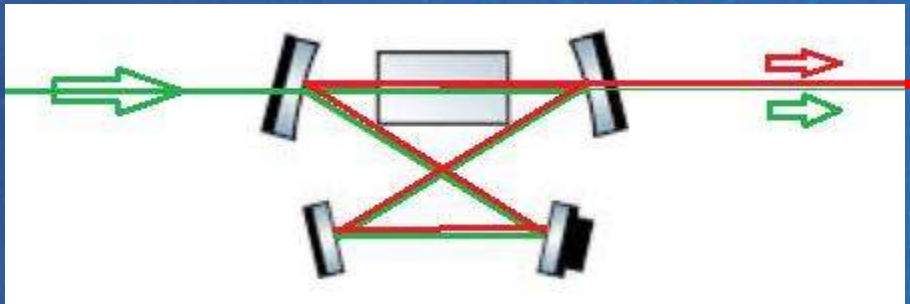
Beating the standard quantum limit: in theory

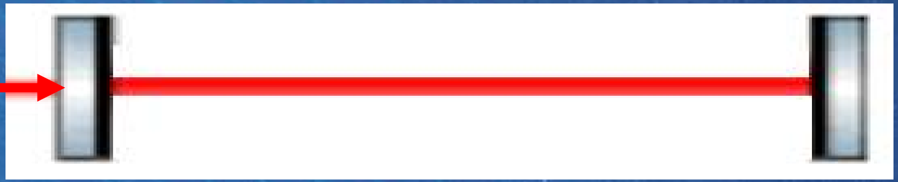
Electric field: $E = X_1\cos(\omega t) + iX_2\sin(\omega t)$



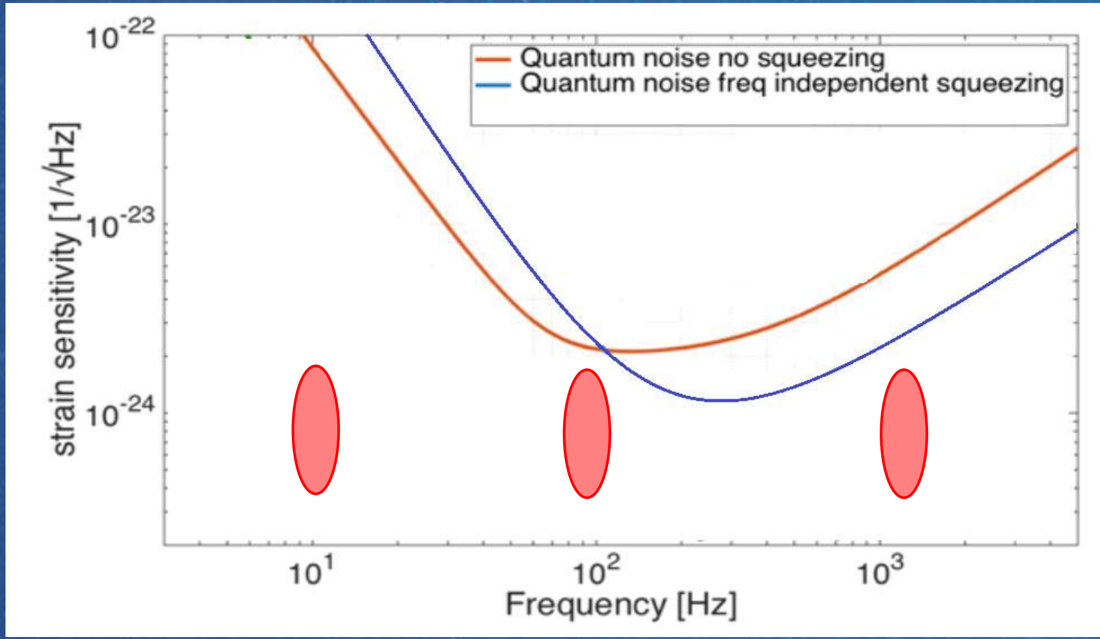
Heisenberg principle: $\Delta X1.\Delta X2 \geq 1$

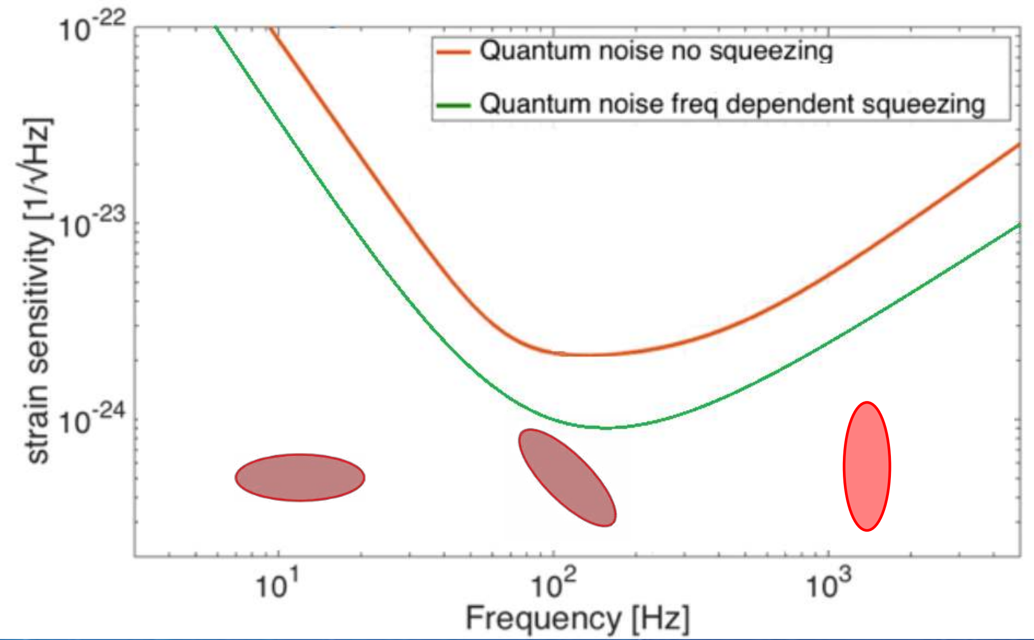
Beating the standard quantum limit: in practice



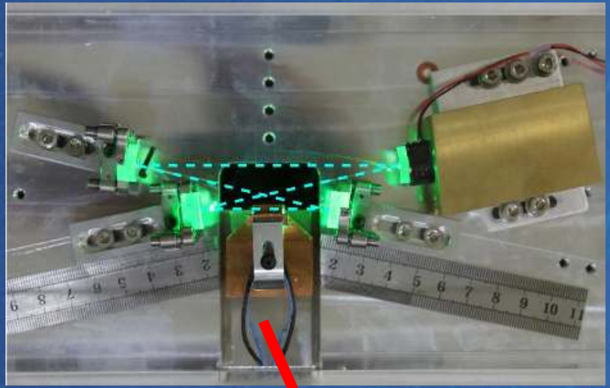


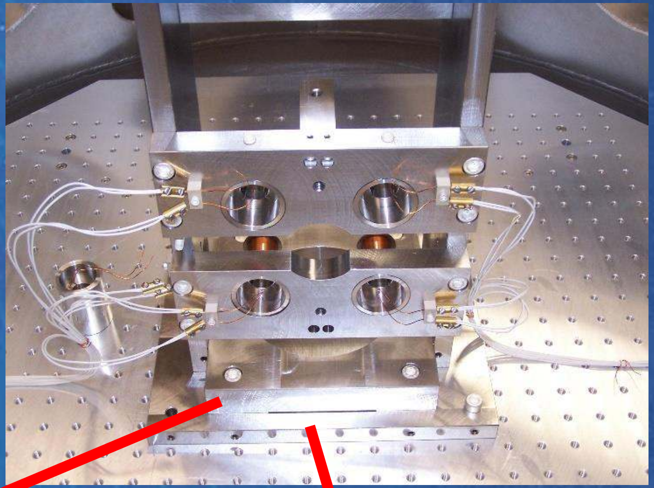
$\omega 1 = \omega 2 + \omega 2$

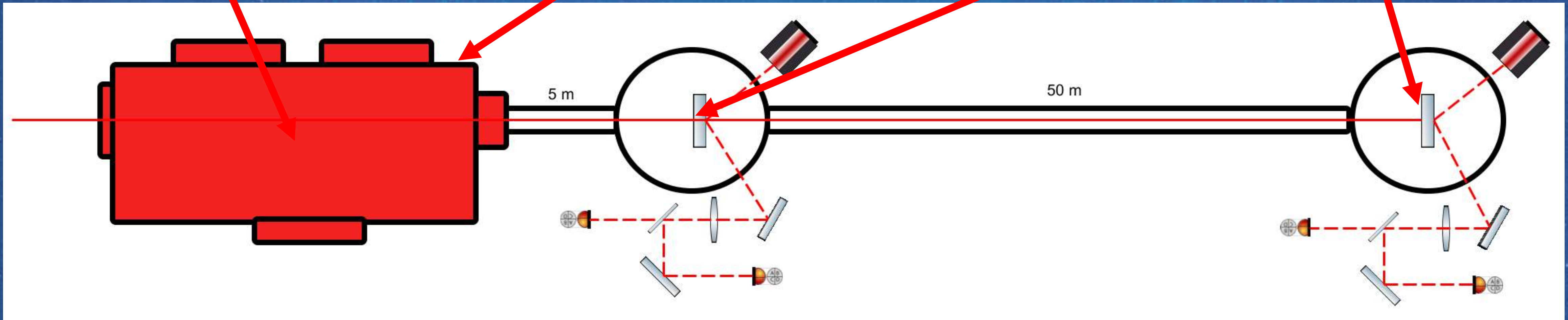


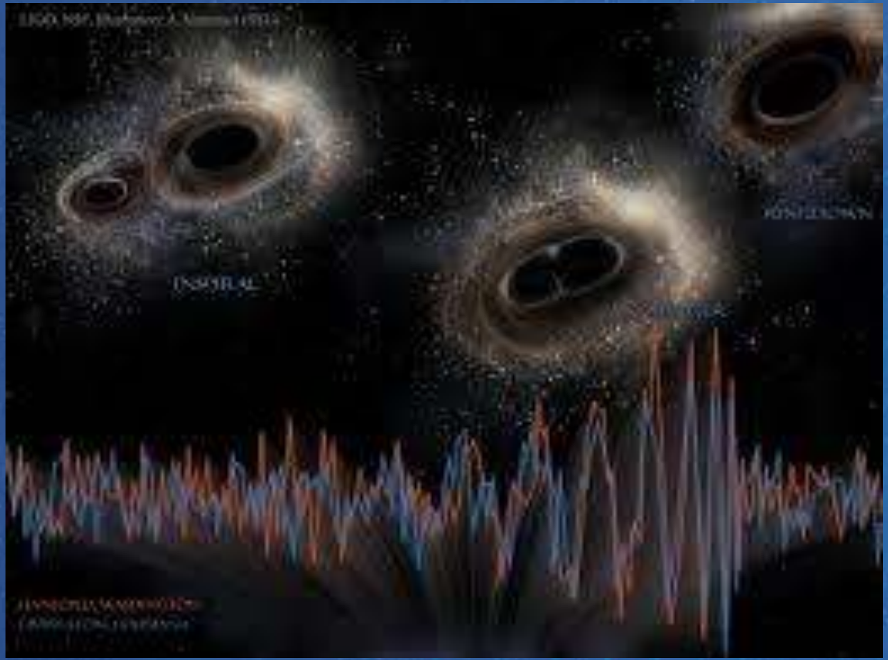


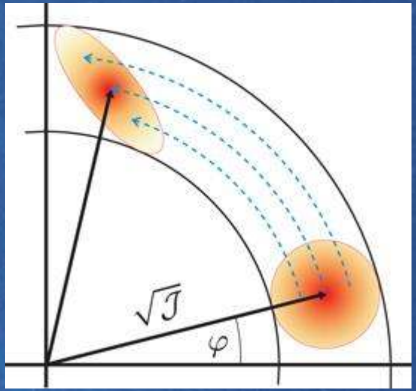
CALVA: CAvity for the Lock of Advanced Virgo



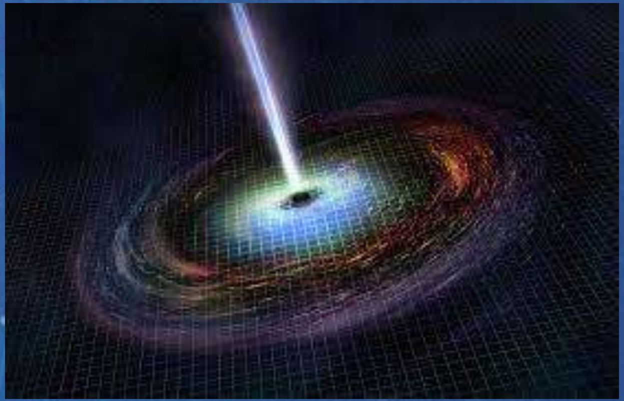


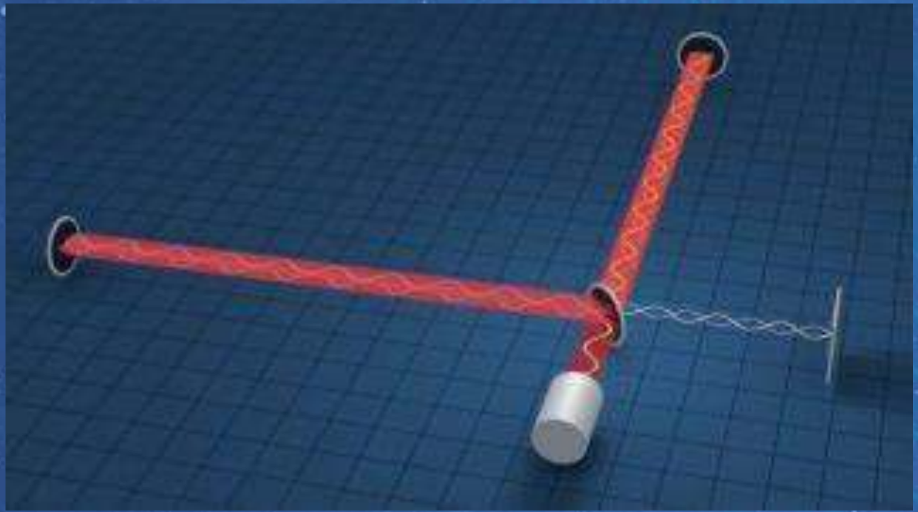


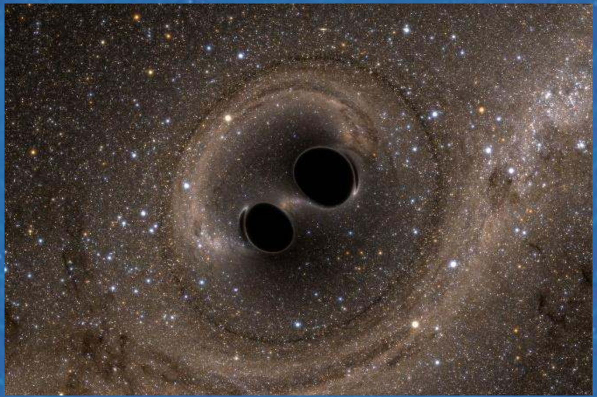


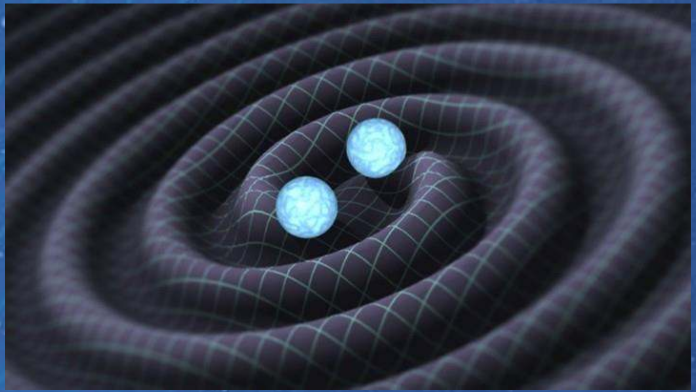


Merci



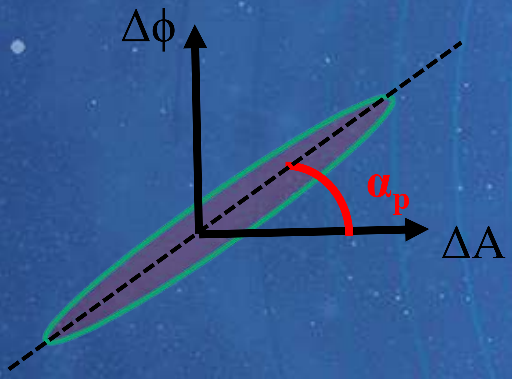


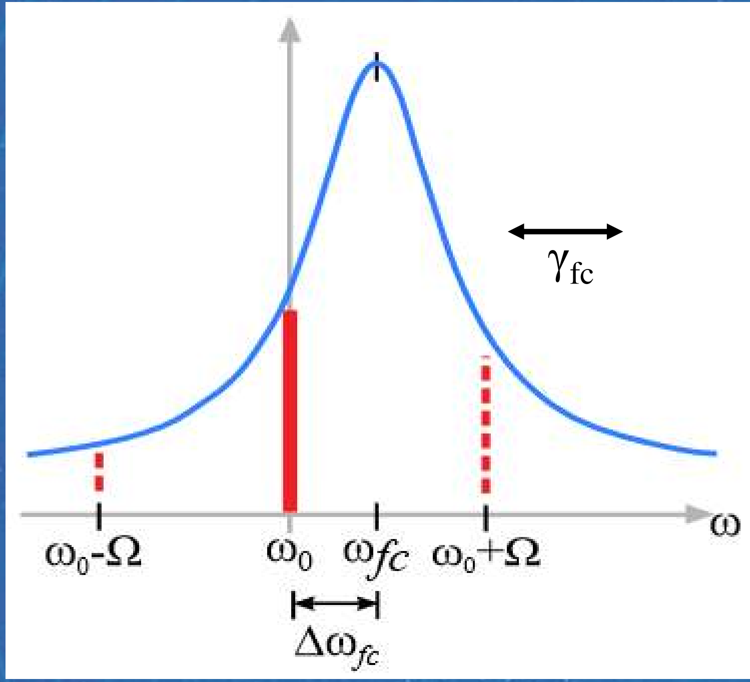




Backup: Ellipse rotation

$$\alpha_p = \arctan\left(\frac{2\gamma_{\rm fc}\Delta\omega_{\rm fc}}{\gamma_{\rm fc}^2 - \Delta\omega_{\rm fc}^2 + \Omega^2}\right)$$

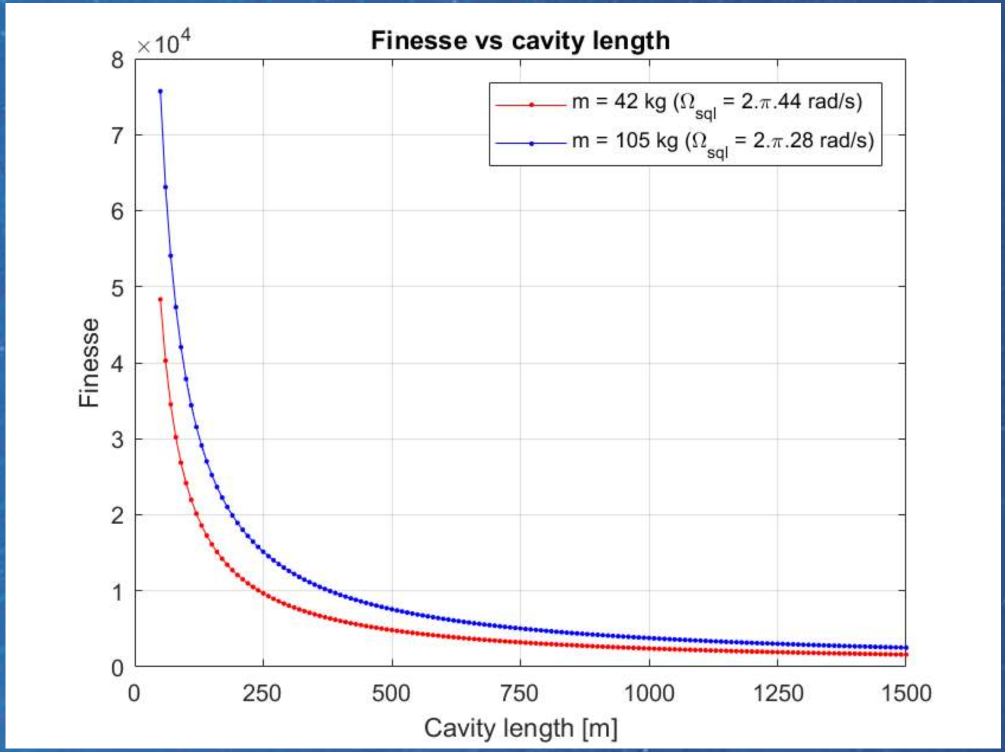




$$\gamma_{fc} = \frac{2.\pi.\Omega_{SQL}}{\sqrt{2}}$$

$$\gamma_{fc} = \frac{\pi.c}{2.L.F}$$

$$\Omega_{\rm SQL\,0} \simeq \frac{8}{c}\sqrt{\frac{P_{\rm arm}\omega_0}{mT_{\rm arm}}}$$



ω_0: carrier field frequency

ω_{fc}: cavity resonance frequency

Ω: sideband frequency

$\Delta\omega_{fc}$: detuning

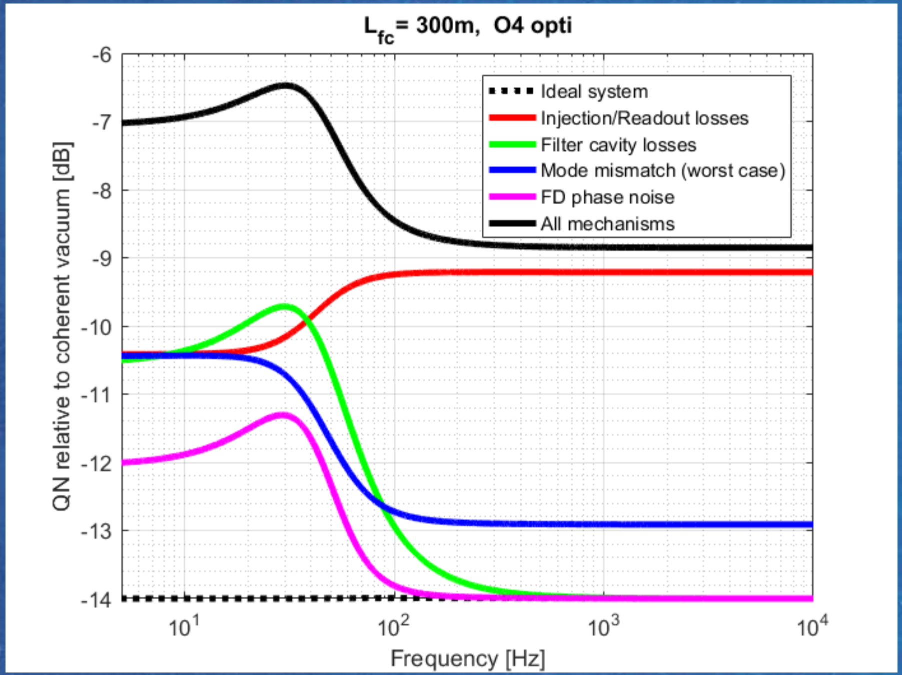
γ_{fc}: half-width-half-maximum linewidth

Backup: squeezing losses

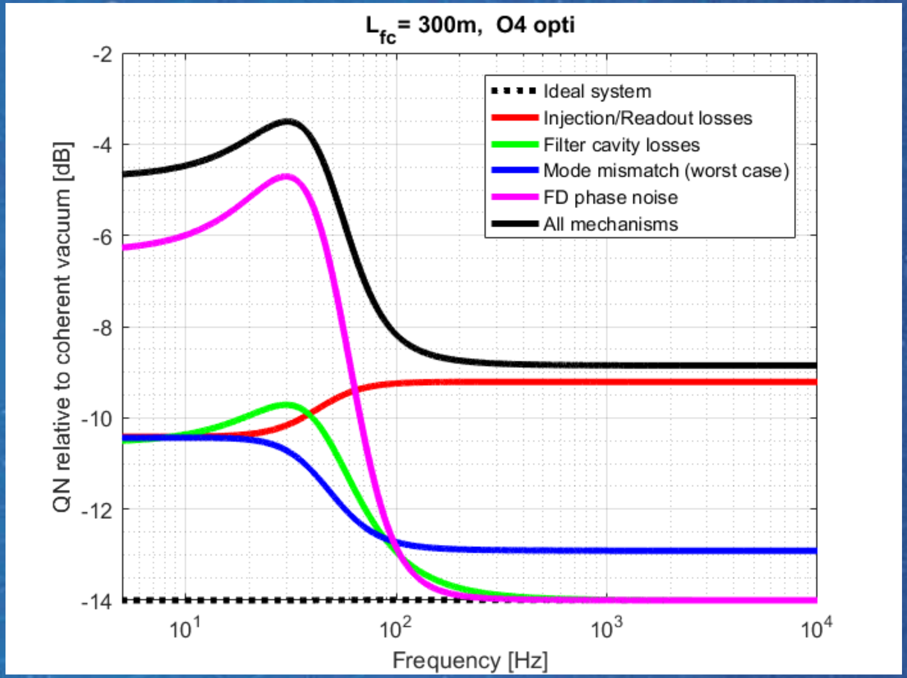
In theory: $\gamma_{fc} = \Delta\omega_{fc}$

In pratice: $\Delta\omega_{fc} = \gamma_{fc}\sqrt{1 - \varepsilon} + \varepsilon_{det}$

With: $$\epsilon = \frac{4}{2 + \sqrt{2 + 2\sqrt{1 + \left(\frac{2.\Omega_{SQL}}{f_{FSR}.\Lambda_{rt}^2}\right)^4}}}$$ and $$\epsilon_{det} = \omega_0.\frac{\epsilon_L}{L_{fc}}$$



FD Phase noise with 1 pm locking accuracy



FD Phase noise with 3 pm locking accuracy